

Design of a Dual-Mode Operation 2-D Periodic Planar Leaky-Wave Antenna

Citation for published version:

Comite, D, Gomez-Guillamon Buendia, V, Fuscaldo, W, Shafiq, Z, Podilchak, SK, Burghignoli, P, Baccarelli, P & Galli, A 2019, Design of a Dual-Mode Operation 2-D Periodic Planar Leaky-Wave Antenna. in *2019 13th European Conference on Antennas and Propagation (EuCAP)*., 8739827, IEEE, 13th European Conference on Antennas and Propagation 2019, Krakow, Poland, 31/03/19.

Link:

[Link to publication record in Heriot-Watt Research Portal](#)

Document Version:

Peer reviewed version

Published In:

2019 13th European Conference on Antennas and Propagation (EuCAP)

Publisher Rights Statement:

© 2019 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

General rights

Copyright for the publications made accessible via Heriot-Watt Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

Heriot-Watt University has made every reasonable effort to ensure that the content in Heriot-Watt Research Portal complies with UK legislation. If you believe that the public display of this file breaches copyright please contact open.access@hw.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.

Design of a Dual-Mode Operation 2-D Periodic Planar Leaky-Wave Antenna

D. Comite¹, V. Gómez-Guillamón Buendía², W. Fuscaldo¹, Z. Shafiq²,
S. K. Podilchak², P. Burghignoli¹, P. Baccarelli³, and A. Galli¹

¹ Department of Information Engineering, Electronics and Telecommunications, Sapienza University of Rome,
Via Eudossiana 18, 00184 Rome, Italy, email: davide.comite@uniroma1.it

² Institute of Sensors, Signals, and Systems, School of Engineering and Physical Sciences Edinburgh Campus,
Heriot-Watt University, Edinburgh EH14 4AS, United Kingdom, email: s.podilchak@hw.ac.uk

³ Department of Engineering, Roma Tre University, 00182 Rome, Italy.

Abstract—In this contribution, we describe the design and the radiation features of a dual-mode operation low-profile, low-cost, wideband antenna. The structure is made by an annular, 2-D radially periodic, leaky-wave antenna enabling the generation of both high-gain beams in the far-field and of nondiffracting waves within the near-field radiative region. This is obtained through the generation of a fast backward spatial harmonic supported by a metal-strip grating placed on a grounded dielectric slab. The radiation can be then described by means of a cylindrical leaky-wave dominating the aperture field of the antenna, whose dispersive behavior is properly taken into account. The high-gain radiation features and the focusing capabilities of the device are experimentally investigated and described. Thanks to the dual-mode capability, the proposed design represents an attractive, simple, and innovative solution for next-generation wireless power transfer devices, for tracking or automotive anti-collision systems as well as for advanced microwave imaging.

Index Terms—Leaky waves, near field, dual-mode antennas, wireless power transfer, microwave imaging.

I. INTRODUCTION

The next-generation of medical imaging and nondestructive testing as well as secure communications, radar and wireless power transfer systems call for the design of low-cost and low-profile antennas enabling advanced performance over both the near- and far-field. Typically, high-directional far-field patterns are obtained by means of arrays of microstrip patch antennas, which can be designed to radiate broadside pencil beams or conical beams steerable along the zenith angle [1]. The elements of the array are conventionally excited by means of parallel or series feeds arrangement, requiring the design of lossy and often complicated feeding networks [2].

Leaky-wave antennas have been demonstrated to be an effective alternative to generate high-gain far-field patterns, thanks to their simple excitation and low-profile intrinsic nature [1, Ch. 11]. At the same time, near-field focused beams can be generated by means of 2-D planar arrays made by horns, patches or by resorting to lens, reflectors, and Fresnel-zone antennas (see, e.g., [3], [4]). A planar array has also been proposed to generate a Bessel beam [5].

A number of alternative design, based on the excitation of the leaky mode supported by an open planar waveguide, have been investigated in the last decade to generate focused beams



Fig. 1. Fabricated and measured planar leaky-wave antenna. Copper color: annular metallic strip arrangement. Dark color: grounded dielectric slab. The structure is made by a slot grating on a grounded dielectric slab (GDS). Strips having width $w = 1$ mm and period $d = 8$ mm define the top PRS. The GDS is made by a dielectric with $\epsilon_r = 2.2$ and thickness $h = 3.14$ mm.

[6], [7] and Bessel beams [8], [9] within the near-field radiative region of the structure. In [9], it has been demonstrated that a collimated, nondiffracting beam, can also be generated through a ‘bull-eye’ antenna [10], [11] (see Fig. 1), which is made by a periodic annular arrangement of metallic strips over a grounded dielectric slab. This class of structures is, indeed, able to support backward leaky waves that can synthesize an inward traveling-wave on the aperture: if properly excited, this kind of wave can in turn effectively describe the cylindrical aperture field distribution responsible for the radiation [12]. Interestingly, by properly designing the feeding system, ‘bull-eye’ antennas can allow for generating higher arbitrary orders of nondiffracting Bessel beams [9], [13].

More recently, the possibility of generating localized waves [14] (i.e., bullet-like pulses) at microwaves by means of a backward cylindrical leaky wave has also been theoretically and experimentally demonstrated by some of the authors in [13] and [15], respectively. In these works, the intrinsic dispersive nature of the complex leaky wavenumber describing the aperture field is taken into account, and its impact on the propagation features of the pulse, with respect to the one generated by the non-planar but very wideband and non-

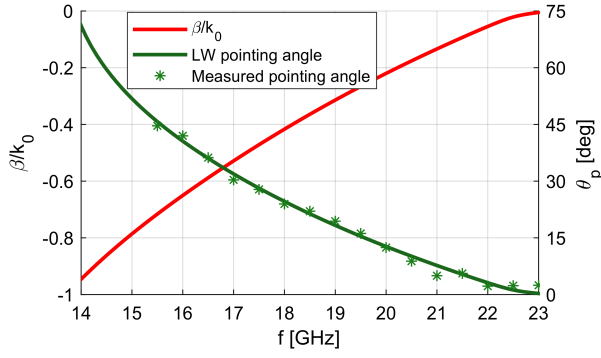


Fig. 2. Left axis: phase constant of the leaky mode supported by the structure in Fig. 1. Right axis: pointing direction of the scanning far-field beam.

dispersive device presented in [16], is discussed.

Generally speaking, the generation of short microwave pulses, can be used to improve the inherently low resolution dictated by the operating wavelength in conventional radar systems. However, due to their relatively large spectral content, such pulses commonly undergo diffractive spreading as they propagate away from the source (see, e.g., [13], [17] and references therein). Therefore, their generation requires for the introduction of innovative solutions. In this frame, we report here the design and the radiative features of a planar wideband leaky-wave antenna, excited by means of a simple vertical coaxial probe, able to provide an uncommon dual-mode operation. The same structure, indeed, can provide a high-gain scanning conical beam [18], [11], as well as Bessel-beams pattern and bullet-like pulses within the nondiffracting region of the antenna. As discussed in the following, this dual-mode operation can be very attractive for the imaging of concealed objects [19], for the future generation of wireless power transfer system, and for advanced far- and near-field microwave imaging [20], [21].

II. ANTENNA DESIGN

A n th-order Bessel beam can be described by the longitudinal electric-field component of a transverse magnetic wave (TM, with respect to the z axis) $E_z(\rho, \phi, z) = E_0 J_n(k_\rho \rho) e^{-jn\phi} e^{-jk_z z}$, E_0 being an amplitude factor and $J_n(\cdot)$ the n th-order Bessel function, ρ and ϕ the radial and azimuthal coordinates of a cylindrical system, k_ρ and k_z the relevant transverse and vertical wavenumbers. If $n = 0$ the beam is azimuthally symmetric (hence $E_\phi = 0$).

We consider a finite circular radiating aperture of radius ρ_a and orthogonal to the z -axis of a cylindrical system with its origin at the aperture center (see Fig. 1 and [9]). To generate the beam, as discussed in [17], [13], [15], one needs to excite an inward cylindrical wave $H_0^{(1)'}(\cdot)$ (first-order derivative of the Hankel function of the first kind). This allows for generating a 0th-order Bessel beam in a region of space close to the z -axis. To synthesize such an inward wave, one can excite an azimuthally symmetric cylindrical TM backward leaky wave [12] supported by an annular slot grating and excited by an azimuthally symmetric source, e.g., a coaxial probe along the

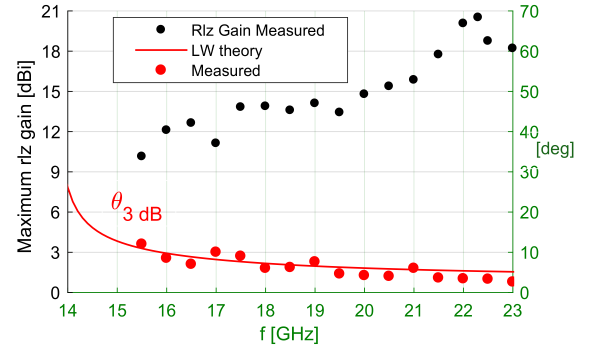


Fig. 3. Left axis: realized gain. Right axis: 3dB beamwidth.

z -axis [9]. To this aim we operate in a frequency range where a fast space harmonic exists (the $n = -1$) and is backward, i.e., a proper leaky wave with $\beta_{-1} \cdot \alpha < 0$. The harmonic propagates as an attenuated outward cylindrical wave with $E_\rho \propto H_0^{(2)'}(k_{\rho,-1}\rho)$, where $k_{\rho,-1} = \beta_{-1} - j\alpha$, with $\beta_{-1} < 0$ and $\alpha > 0$. Since, in general, $H_0^{(2)}(z) = -H_0^{(1)}(-z)$, the desired aperture distribution is thus obtained [13].

To illustrate the dual-mode operation capability of the proposed antenna, we consider the bull-eye design presented in [9], whose geometrical features are reported in Fig. 1. The structure is properly designed to support an $n = -1$ fast spatial harmonic over an aperture having radius $\rho_a = 14$ cm. Figure 2 reports the normalized phase constant (solid line, left axis) versus the frequency of the linearized structure (see [9] for further details on the linearization aspects). The normalized attenuation constant (not reported here) has a quite stable behavior versus the frequency and is between about 0.02 and 0.035. As experimentally investigated in [11], the antenna radiates a high-directional conical beam, scanning with f and with the main beam covering a wide portion of the upper hemisphere, from about 2° to 70° (see Fig. 2, right axis). The near-field radiated by the prototype has been, instead, investigated in [9], and will be summarized in section III.

III. EXPERIMENTAL CHARACTERIZATION

The dual-mode antenna prototype was measured in a calibrated anechoic chamber. A picture of the structure is reported in Fig. 1, while the impedance bandwidth (well below -10 dB from 14 GHz to 22 GHz) and the configuration of the feed can be found in [9]. Figure 3 reports the main features of the far-field pattern generated by the proposed antenna. The measured maximum realized gain vs. f (black dots, left axis) confirms its high-gain features. Also, its -3 dB beam-width is well predicted by the leaky-wave formula [1, Ch. 11, eqs. 11.2 and 11.3] (red curves, right axis). The beam pointing angle in Fig. 2 (green curves, right axis) is in excellent agreement with the theory.

The normalized z and ρ components of the electric field along the xz plane are reported in Figs. 4 and 5. They are collected moving the probe from 6 cm up to a distance $z_0 = 31$ cm from the antenna aperture; both amplitude and

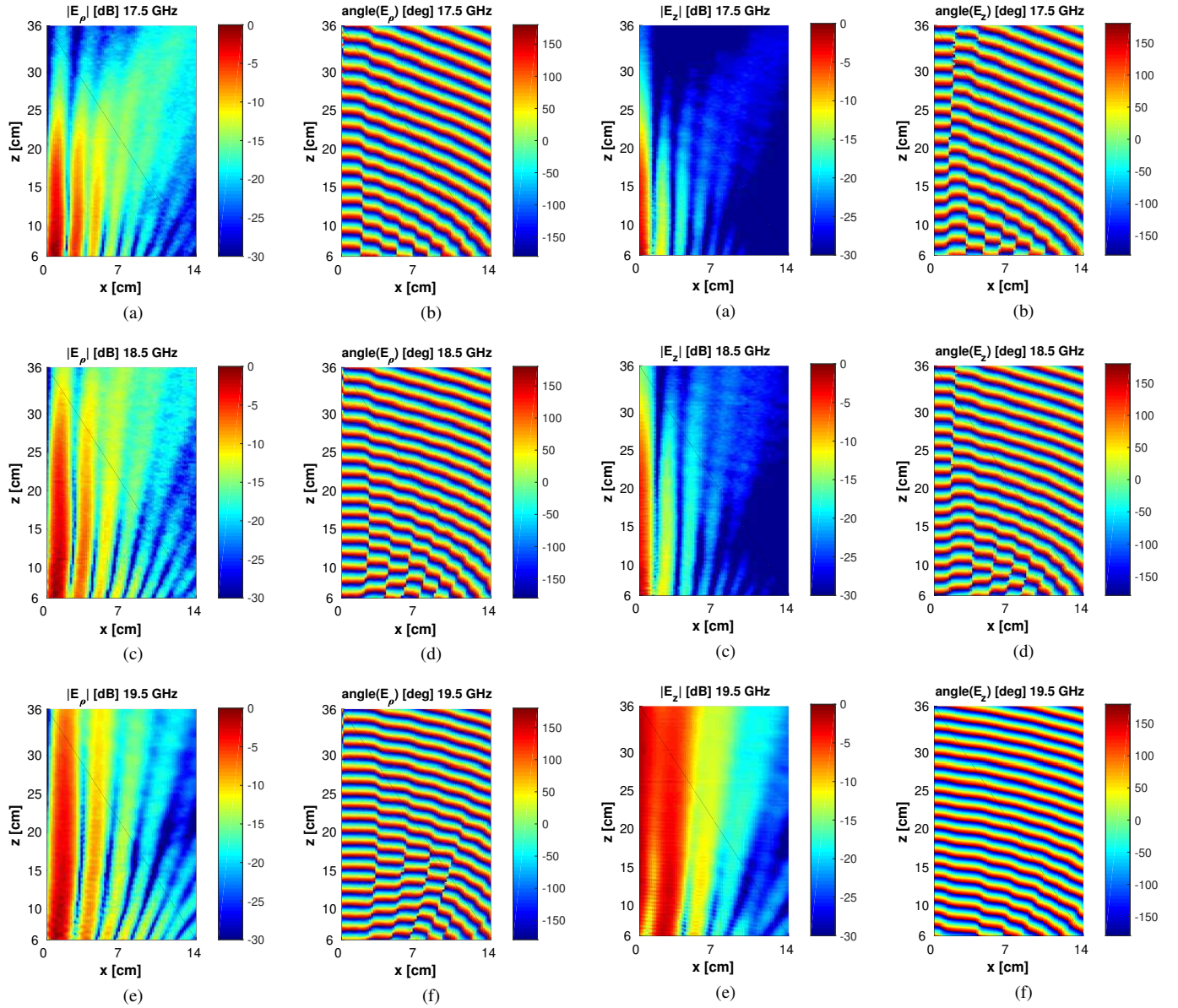


Fig. 4. Measured longitudinal 2-D profile of the near field radiated in the xz -plane (i.e., $\phi = 0$) up to $z_{\text{NDR}} = 31$ cm. (a), (c), (e) amplitude and (b), (d), (f) phase of the ρ -component for 17.5, 18.5, 19.5 GHz, respectively.

phase are reported for three different frequencies (see captions, further frequency values and transverse profiles of the field can be found in [9]). As discussed in [9], the antenna is able to generate well defined Bessel-beam patterns over a wide frequency range, enabling the generation of a bullet-like pulse [16] by means of the planar antenna. We should note that, while in far field a variation of the frequency generates a scanning beam over the zenith angle, in the near field it tunes the nondiffracting range of the system [13], and it mainly determines the limit distance beyond which the beam starts to diffract losing the Bessel-like collimated character.

As experimentally demonstrated in [15], the wideband character of the focusing features of the bull-eye antenna can allow for generating localized energy in the microwave frequency

region. However, both the inherent wavenumber dispersion and complex nature of the leaky wavenumber responsible for the radiation unavoidably affects the radiated near field [13]. To assess the uncommon dual-mode operation enabled by the antenna, we exploit here the dispersion engineering approach proposed in [15] to generate a bullet-like pulse within the radiative near-field region of the structure. To this aim, the phase patterns presented in Figs. 4 and 5 have been properly post-processed to provide the requested coherency before performing a fully vector time-domain inversion of the measured near-field maps [15]. Figure 6 reports the amplitude of both the z and ρ components of the field at a time instant $t_0 = 1.1$ ns. The focused character of the pulse is manifest, paving the way for the design of next-generation of highly efficient microwave imaging system based on the use of

Fig. 5. As in Fig. 4 but for the z component of the field.

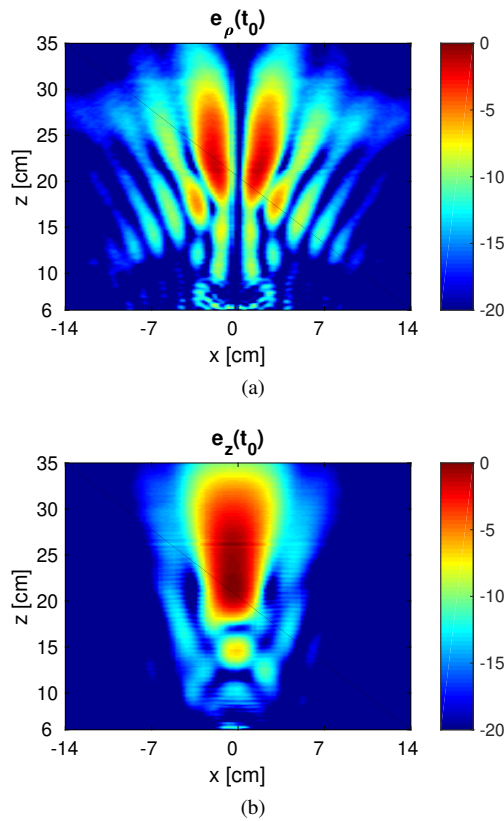


Fig. 6. Measured normalized leaky pulse field amplitude (dB) over the xz plan: (a) E_ρ (b) E_z for a fixed time instant $t_0 = 1.1$ ns.

localized energy, as opposed to the more common systems based on the nondirectional character requested to achieve cross-range resolution by means of a synthetic aperture.

IV. CONCLUSION

A wideband radially-periodic, dual-mode operation, leaky-wave antenna fed by a simple source and supporting a fast backward cylindrical leaky wave, has been proposed for generating a highly directional far-field conical beam as well as a nondiffracting beam within the radiative nearfield of the structure. Thanks to the traveling-wave nature of the approach, the capabilities of this class of devices of generating localized pulses in the microwave range have been summarized. The unconventional performance of the proposed devices can offer new ways for the designs of multifunctional antennas: e.g., for wireless power systems requiring both power and data transfer/transmission, and for anti-collision radars with near-field data connectivity. More involved geometry of the aperture will be studied, which can allow for controlling the dispersive behavior of the leaky wavenumber and of the scanning losses. Besides, the use of larger fractional bandwidths will potentially enable for the generation of very short pulses, an attractive features that can open unprecedented possibilities for microwave near-field imaging.

REFERENCES

- [1] J. L. Volakis, *Antenna Engineering Handbook*. New York, NY: McGraw Hill, 2007, 4th Ed.
- [2] D. M. Pozar and D. H. Schaubert, *Microstrip Antenna Array Design*. Wiley-IEEE Press, 1995.
- [3] R. Hansen, "Focal region characteristics of focused array antennas," *IEEE Trans. Antennas Propag.*, vol. 33, no. 12, pp. 1328–1337, Dec. 1985.
- [4] A. Buffi, P. Nepa, and G. Manara, "Design criteria for near-field-focused planar arrays," *IEEE Antennas Propag. Mag.*, vol. 54, no. 1, pp. 40–50, Feb. 2012.
- [5] P. Lemaître-Auger, S. Abielmona, and C. Caloz, "Generation of Bessel beams by two-dimensional antenna arrays using sub-sampled distributions," *IEEE Trans. Antennas Propag.*, vol. 61, no. 4, pp. 1838–1849, Apr. 2013.
- [6] J. L. Gómez-Tornero, D. Blanco, E. Rajo-Iglesias, and N. Llombart, "Holographic surface leaky-wave lenses with circularly-polarized focused near-fields—Part I: Concept, design and analysis theory," *IEEE Trans. Antennas Propag.*, vol. 61, no. 7, pp. 3475–3485, Apr. 2013.
- [7] A. J. Martínez-Ros, J. L. Gómez-Tornero, V. Losada, F. Mesa, and F. Medina, "Non-uniform sinusoidally modulated half-mode leaky-wave lines for near-field focusing pattern synthesis," *IEEE Trans. Antennas Propag.*, vol. 63, no. 3, pp. 1022–1031, Dec. 2015.
- [8] M. Ettorre and A. Grbic, "Generation of propagating Bessel beams using leaky-wave modes," *IEEE Trans. Antennas Propag.*, vol. 60, no. 8, pp. 3605–3613, Aug. 2012.
- [9] D. Comite, W. Fuscaldo, S. K. Podilchak, P. D. Hilario Re, V. Gómez-Guillamón Buendía, P. Burghignoli, P. Baccarelli, and A. Galli, "Radially periodic leaky-wave antenna for Bessel-beam generation over a wide frequency range," *IEEE Trans. Antennas Propag.*, vol. 66, no. 6, pp. 2828–2843, Jun. 2018.
- [10] S. K. Podilchak, P. Baccarelli, P. Burghignoli, A. P. Freundorfer, and Y. M. Antar, "Analysis and design of annular microstrip-based planar periodic leaky-wave antennas," *IEEE Trans. Antennas Propag.*, vol. 62, no. 6, pp. 2978–2991, Jun. 2014.
- [11] D. Comite, V. G. Buenda, S. K. Podilchak, D. D. Ruscio, P. Baccarelli, P. Burghignoli, and A. Galli, "Planar antenna design for omnidirectional conical radiation through cylindrical leaky waves," *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 10, pp. 1837–1841, Oct. 2018.
- [12] A. Ip and D. R. Jackson, "Radiation from cylindrical leaky waves," *IEEE Trans. Antennas Propag.*, vol. 38, no. 4, pp. 482–488, Apr. 1990.
- [13] W. Fuscaldo, D. Comite, A. Boesso, P. Baccarelli, P. Burghignoli, and A. Galli, "Focusing leaky waves: A class of electromagnetic localized waves with complex spectra," *Phys. Rev. Appl.*, vol. 9, no. 5, p. 054005, 2018.
- [14] R. W. Ziolkowski, "Localized transmission of electromagnetic energy," *Phys. Rev. A*, vol. 39, no. 4, p. 2005, 1989.
- [15] D. Comite, W. Fuscaldo, S. Podilchak, V. Gómez-Guillamón Buendía, P. Hilario Re, P. Baccarelli, P. Burghignoli, and A. Galli, "Microwave generation of X-waves by means of a planar leaky-wave antenna," *Appl. Phys. Lett.*, vol. 113, no. 14, p. 144102, 2018.
- [16] N. Chiotellis, V. Mendez, S. M. Rudolph, and A. Grbic, "Experimental demonstration of highly localized pulses (X waves) at microwave frequencies," *Phys. Rev. B*, vol. 97, no. 8, p. 085136, 2018.
- [17] S. C. Pavone, A. Mazzinghi, A. Freni, and M. Albani, "Comparison between broadband Bessel beam launchers based on either Bessel or Hankel aperture distribution for millimeter wave short pulse generation," *Opt. Express*, vol. 25, no. 16, pp. 19 548–19 560, 2017.
- [18] C. A. Allen, C. Caloz, and T. Itoh, "Leaky-waves in a metamaterial-based two-dimensional structure for a conical beam antenna application," in *Microwave Symp. Digest, 2004 IEEE MTT-S International*, vol. 1. IEEE, 2004, pp. 305–308.
- [19] A. Mazzinghi and A. Freni, "Simultaneous generation of pseudo-Bessel vortex modes with a RLSA," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 1747–1750, 2017.
- [20] M. Boyarsky, T. Sleasman, L. Pulido-Mancera, T. Fromenteze, A. Pedross-Engel, C. M. Watts, M. F. Imani, M. S. Reynolds, and D. R. Smith, "Synthetic aperture radar with dynamic metasurface antennas: a conceptual development," *J. Opt. Soc. Am. A*, vol. 34, no. 5, pp. A22–A36, 2017.
- [21] J. Hunt, J. Gollub, T. Driscoll, G. Lipworth, A. Mrozack, M. S. Reynolds, D. J. Brady, and D. R. Smith, "Metamaterial microwave holographic imaging system," *J. Opt. Soc. Am. A*, vol. 31, no. 10, pp. 2109–2119, 2014.